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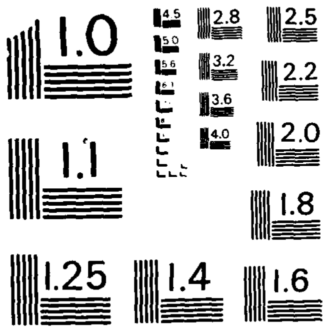

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1983-84 Connecticut 45-Hz-Band Field-Strength Measurements

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Newport, Rhode Island / New London, Connecticut

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Preface

This report was prepared under NUSC Project No. A59007, "ELF Propagation RDT&E" (U), Principal Investigator, P. R. Bannister (Code 3411), Navy Program Element No. 11401N and Project No. XD792, Space and Naval Warfare Systems Command (SPAWARSYSCOM), Capt. R. Koontz (Code PDW 110-3), Program Manager ELF Communications.

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(U) The results of 23 days of 45-Hz-band Connecticut measurements taken during 1983-84 are discussed in this report. The main result is that the average measured field strengths are in excellent agreement (in both amplitude and relative phase) with previous 45-Hz-band measurement results.

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INTRODUCTION

Since June 1970, we have made extremely low frequency (ELF) measurements of the transverse horizontal magnetic field strength (H_ϕ) received in Connecticut.[1-15] The local measurement site from June 1970 to October 1971 was in the Nehantic State Forest, East Lyme, CT. From October 1971 through November 1975, it was located in Hammonassett State Park, Madison, CT. Since July 1976, the AN/BSR-1 ELF receiver has been located at the Naval Underwater Systems Center (NUSC), at New London, CT. The loop receiving antenna is now located at Fishers Island, NY (about 10 km from New London). The receiver and receiving antenna are connected by means of a microwave link from Fishers Island to New London.

The AN/BSR-1 receiver is composed of an AN/UYK-20 minicomputer, a signal timing and interface unit (STIU), a rubidium frequency time standard, two magnetic-tape recorders, and a preamplifier.

The transmission source for these farfield (1.6-Mm range) measurements is the U.S. Navy's ELF Wisconsin Test Facility (WTF), located in the Chequamegon National Forest in north-central Wisconsin, about 8 km south of the village of Clam Lake. The WTF consists of two 22.5-km antennas; one antenna is located approximately in the north-south (NS) direction and one is located approximately in the east-west (EW) direction. Each antenna is grounded at both ends. The electrical axis of the WTF EW antenna is 118 deg east of north at 45 Hz and 114 deg east of north at 75 Hz. The electrical axis of the WTF NS antenna is 11 deg east of north at 45 Hz and 14 deg east of north at 75 Hz. The WTF array can be steered electrically toward any particular location. Its radiated power is approximately 0.5 W at 45 Hz and 1 W at 75 Hz.

Since July 1976, nearly all of the Connecticut field-strength measurements have been taken at a WTF transmitting frequency of 76 ±4 Hz.[5-15] In this report we will discuss the results of the limited amount of 45-Hz-band data taken during 1983-84 and compare them with previous 45-Hz-band measurement results.

THEORY

For measurement distances greater than 1.5L and greater than an earth wavelength, λ_e, the (direct path) H_ϕ component produced by the WTF EW antenna (of length L) can be expressed as[16,17]

$$H_\phi \sim - \frac{ILf(L)G(t)\cos\phi e^{-\alpha\rho}}{2\pi\gamma_e\rho^3}\left[\left(- \frac{i\pi x}{2}\right)H_1^{(2)}(x)f(x)S\right] \quad \text{A/m} , \tag{1}$$

where

I = WTF EW antenna current (300 A),

L = WTF EW antenna length (2.25×10^4 m),

ϕ = azimuth angle (deg),

ρ = great-circle distance between WTF and receiver (m),

h = effective ionospheric reflecting height (m),

α = earth-ionosphere waveguide attenuation rate (Np/m),

v = earth-ionosphere waveguide phase velocity (m/s),

c = velocity of light in free space ($\sim 3 \times 10^8$ m/s),

S = spherical earth spreading factor,

a = radius of the earth ($\sim 6.37 \times 10^6$ m),

$\gamma_e \approx (i\omega\mu_0\sigma_e)^{1/2} = (1 + i)/\delta_e$ = propagation constant in the earth beneath the WTF EW antenna (meters^{-1}),

$\delta_e \approx \sqrt{2/(\omega\mu_0\sigma_e)}$ = skin depth in the earth beneath the WTF EW antenna (m),

$\lambda_e = 2\pi\delta_e$ = wavelength in the earth (m),

σ_e = effective conductivity beneath the WTF EW antenna (2.8×10^{-4} S/m at 45 Hz and 3.2×10^{-4} S/m at 75 Hz),

$H_0^{(2)}(x)$ = Hankel function of the second kind, order zero, and argument x, and

$H_1^{(2)}(x)$ = Hankel function of the second kind, order one, and argument x.

For $\rho \leq 2$ Mm, the spherical earth spreading factor $S \approx 1$. For $2 \leq \rho \leq 19$ Mm,

$$S = \sqrt{\frac{\rho/a}{\sin(\rho/a)}} \; , \tag{2}$$

while, at the antipode ($\rho = \pi a = 20$ Mm),[18,19]

$$S = \sqrt{\frac{\pi x}{2}} \; , \tag{3}$$

where

$$x = k\rho(c/v) = \frac{2\pi\rho}{\lambda}(c/v) \; . \tag{4}$$

The functions $f(L)$, $f(x)$, and $G(t)$ are defined by

$$f(L) = 1 + 2\left(\frac{L}{2\rho}\right)^2\left(1 - \frac{15}{4}\sin^2\phi\right) \; , \tag{5}$$

$$f(x) = 1 - x\left(\frac{H_0^{(2)}(x)}{H_1^{(2)}(x)}\right) \; , \tag{6}$$

and

$$G(t) = \left(\frac{2t}{\pi}\right)\coth t + \left(1 - \frac{2}{\pi}\right)t^2 \operatorname{csch}^2 t \; , \tag{7}$$

where

$$t = \frac{\pi\rho}{2h(c/v)^2} \; . \tag{8}$$

When $t < 0.5$, $G(t) \sim 1$. When $t > 2.5$, $G(t) \sim 2t/\pi$, $\rho >> L$, and $f(L) \sim 1$. Therefore, when $t > 2.5$, equation (1) reduces to

$$H_\phi \sim - \frac{IL \cos\phi e^{-\alpha\rho}}{2\pi\gamma_e h(c/v)^2\rho^2}\left[\left(- \frac{i\pi x}{2}\right)H_1^{(2)}(x)f(x)S\right] \text{ A/m} \; . \tag{9}$$

When $x > 1.6$ (approximately 1.4 Mm at 45 Hz and 0.85 Mm at 75 Hz[16]),

$$\left[\left(- \frac{i\pi x}{2}\right)H_1^{(2)}(x)f(x)\right] \sim ix\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \tag{10}$$

and equation (9) reduces to

$$H_\phi \sim - \frac{ILS \cos\phi e^{-\alpha\rho}}{2\pi\gamma_e h(c/v)^2\rho^2}\, ix\sqrt{\frac{\pi x}{2}}\, e^{-i(x-\pi/4)} \text{ A/m} \; . \tag{11}$$

Furthermore, when $x > 1.6$, but $\rho \leq 19$ Mm, equation (11) becomes

$$H_\phi \sim - \frac{\pi IL \cos\phi e^{-\alpha\rho}}{\gamma_e h\lambda^{3/2}(c/v)^{1/2}}\left(\frac{e^{-i(x-\pi/4)}}{\sqrt{a \sin(\rho/a)}}\right) \text{ A/m} \; , \tag{12}$$

while, at the antipode ($\rho = \pi a$), the magnitude of H_ϕ is equal to (from equation (11))

$$|H_\phi| \sim \frac{\pi^2 IL(\delta_e/\sqrt{2})\cos\phi e^{-2\pi a}}{h\lambda^2} \quad \text{A/m} . \tag{13}$$

The direct path H_ϕ component produced by the WTF antenna array can be obtained from equations (1), (9), (11), (12), or (13) by replacing cos ϕ with $F(\phi)/B$, the WTF array pattern factor[6,20] (which equals unity in the direction of the EW antenna axis). For $x > 1.6$ and $\rho \leq 19$ Mm, the direct-path H_ϕ component produced by the WTF antenna array (equation (12)) also can be expressed as

$$20 \log H_\phi \sim K + 20 \log E - \alpha\rho - 10 \log\left[a \sin\left(\frac{\rho}{a}\right)\right]$$

$$+ 20 \log\left(\frac{F(\phi)}{B}\right) \text{ dBA/m} , \tag{14}$$

where K = -143.7 dB at 45 Hz and -139.2 dB at 75 Hz and

$$E = \left(h_{KM}\sqrt{\sigma_e}\sqrt{c/v}\right)^{-1}$$

is defined as the earth-ionosphere waveguide excitation factor. In equation (14), h is in km, ρ and a are in Mm, and α is in dB/Mm.

Plotted in figures 1* and 2 versus range are predicted 45-Hz and 75-Hz values of the direct path H_ϕ component produced by the omnidirectionally-phased (omni) WTF array (20 log $F(\phi)/B \sim +0.8$ dB) during daytime, transition period (TP), and nighttime propagation conditions. Equations (13) and (14) and the all-paths average values of attenuation rates and excitation factors[21] were used for these predictions. Note that the predicted antipodal field strengths are approximately equal to the 7- to 9-Mm field strengths at 45 Hz and the 8- to 11-Mm field strengths at 75 Hz (depending on propagation conditions). Also, there is a crossover point (approximately 6 Mm at 75 Hz and 11 Mm at 45 Hz) where the predicted field strengths are identical during daytime, transition period, and nighttime propagation conditions.

For distances from approximately 5 to 20 Mm (depending on frequency and propagation conditions), there also will be a standing-wave pattern set up due to interference between the direct (short-path) and "round-the-world" (long-path) field-strength components.

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*All figures have been placed together at the end of this report.

PAST 45-Hz-BAND RESULTS

Presented in tables 1 and 2 are summaries of the 45-Hz-band interpretations for ambient daytime and nighttime propagation conditions.[21] The values of the attenuation rate and excitation factor were inferred from the limited propagation measurements taken over various paths from 1970 through 1972.[22] The average daytime and nighttime attenuation rates inferred from these measurements were 1.03 and 0.74 dB/Mm, respectively, while the excitation factors were +0.7 dB during the day and -2.5 dB at night.

A convenient quantity to describe the characteristics of the lower ionosphere is the conductivity parameter ω_r, which is defined by

$$\omega_r = \omega_0^2/\nu \ , \tag{15}$$

where ω_0 is the (angular) plasma frequency of the electrons and ν is the effective collision frequency.[23] The plasma frequency at a particular height is determined directly by the electron-density profile. Experience has shown that simple exponential models of the electron density and collision frequency in the lower ionosphere are adequate to describe extremely low frequency/very low frequency/low frequency (ELF/VLF/LF) radiowave propagation in most cases. The exponential height profile of the conductivity parameter ω_r successfully employed by Wait and Spies[24] is

$$\omega_r(z) = 2.5 \times 10^5 \exp[-\beta(H - z)] \ , \tag{16}$$

where β is equal to $1/\zeta$, ζ is the scale height, and H is the (arbitrary) reference height.

Table 1. 1970-72 45-Hz-Band Ambient Daytime Interpretations

Path	Date	α_D (dB/Mm)	E_D (dB)	c/v	h (km)	ζ (km)	β (km^{-1})	H (km)
California/Hawaii	7/70	1.20	1.4	1.37	43.6	3.88	0.26	70.0
Utah/Hawaii	3/71-4/71	1.20	1.4	1.37	43.6	3.88	0.26	70.0
North Carolina/ Virgin Islands	3/71-4/71	1.10	0.9	1.34	46.4	3.80	0.26	72.2
All Sites/Norway	10/71-11/71	0.90	1.1	1.30	46.4	3.13	0.32	67.6
Alaska/Saipan	5/72	0.90	0.0	1.29	52.5	3.55	0.28	76.6
WTF/Greece	5/72	0.80	0.0	1.27	53.0	3.20	0.31	74.7
WTF/Norway	5/72	1.00	0.0	1.32	52.0	3.89	0.26	78.4
Averages		1.03	+0.7	1.32	48.2	3.62	0.28	72.8

Table 2. 1970-72 45-Hz-Band Ambient Nighttime Interpretations

Path	Date	α_N (dB/Mm)	E_N (dB)	c/v	h (km)	ζ (km)	β (km^{-1})	H (km)	h_E (km)
California/Hawaii	7/70	0.7	-3.3	1.13	82.3	3.00	0.33	102.6	104.7
Utah/Hawaii	3/71-4/71	0.8	-2.3	1.15	72.8	3.04	0.33	93.4	95.5
North Carolina/Virgin Islands	3/71-4/71	0.8	-2.2	1.15	72.0	3.00	0.33	92.3	94.4
All Sites/Norway	10/71-11/71	0.9	-0.1	1.16	56.1	2.63	0.38	73.9	75.7
Alaska/Saipan	5/72	0.7	-3.3	1.13	82.3	3.00	0.33	102.6	104.7
WTF/Greece	5/72	0.6	-3.3	1.11	82.9	2.59	0.39	100.5	102.3
WTF/Greece	5/72	0.7	-3.3	1.13	82.3	3.00	0.33	102.6	104.7
Averages		0.74	-2.5	1.14	75.8	2.89	0.35	95.4	97.4

Also included in tables 1 and 2 are representative ionospheric parameters for each propagation path considered.[21] These parameters include the reflection height h, scale height ζ, inverse scale height β, and reference height H. For nighttime propagation (table 2), the height of the E-layer (h_E) also is included.[21]

For ambient daytime conditions, the individual path variations in the reflection height, inverse scale height, and the reference height of the equivalent exponential ionosphere profile were 43 to 53 km, 0.26 to 0.32 km^{-1}, and 67 to 78 km, respectively.

For ambient nighttime propagation conditions, the individual path variations in h, β, and H were 56 to 83 km, 0.33 to 0.39 km^{-1}, and 74 to 103 km, respectively.

1983-84 45-Hz-BAND MEASUREMENTS

During 1983 and 1984, reliable field-strength data were obtained on 23 days at the Connecticut site. The daily plots of signal strength (both amplitude and relative phase) versus Greenwich Mean Time (GMT) (in 1-hr increments) are presented in figures 3 through 8, while the daily field-strength averages are presented in tables 3 and 4. These data are broken up into four time periods, which are representative of nighttime, sunrise transition period (SRTP), daytime, and sunset transition period (SSTP) propagation conditions. The data are all normalized to a WTF antenna current of 300 A and an array phasing angle of 291 deg.

Referring to tables 1 and 2, we see that the average daytime and nighttime attenuation rates inferred from the 1970-72 45-Hz-band measurements were 1.05 and 0.74 dB/Mm, respectively, while the excitation factors were +0.7 dB

Table 3. January 1983 44-Hz Daytime Connecticut Field-Strength Averages (Normalized to I = 300 A and ψ = 291 deg)

Date	H_ϕ (dBA/m)
1/10/83	-145.6
1/11/83	-145.7
1/12/83	-145.6
1/13/83	-145.9
1/14/83	-146.8
1/83 Average	-145.9
Predicted 44-Hz Average	-145.9

Table 4. 45-Hz-Band Connecticut Field-Strength Averages
(Normalized to I = 300 A and ψ = 291 deg)

Frequency (Hz)	Date	Night H_ϕ (dBA/m)	SRTP H_ϕ (dBA/m)	Day H_ϕ (dBA/m)	SSTP H_ϕ (dBA/m)	$\Delta\phi$ (deg)
44	12/16/83	-149.0	-147.5	-146.5(1)	-	10.4
44	12/17/83	-149.1	-147.8	-146.1	-147.1	9.7
44	12/18/83	-148.5	-147.8	-146.0	-146.8	5.0
44	Averages	-148.9	-147.7	-146.1	-146.9	8.4
44	3/17/84	-148.7	-147.6	-146.3	-147.6	11.8
44	3/18/84	-149.2	-147.2	-145.9	-147.2	23.6
44	3/19/84	-148.9	-147.1	-145.9	-147.0	16.8
44	Averages	-148.9	-147.3	-146.1	-147.2	17.4
44	9/15/84	-148.6	-147.6	-145.9	-146.4	17.3
44	9/16/84	-148.2	-148.6	-145.9	-146.5	18.3
44	9/17/84	-148.8	-148.4	-	-148.1	6.3
44	Averages	-148.5	-148.2	-145.9	-147.0	14.0
42	10/6/84	-149.1	-148.1	-146.3	-147.8	16.5
42	10/7/84	-148.5	-147.6	-146.7	-147.3	-1.0
42	10/8/84	-149.2	-147.7	-	-	28.0
42	Averages	-148.9	-147.8	-146.5	-147.5	14.5
44	10/13/84	-148.6	-147.2	-146.0	-148.1	24.5
44	10/14/84	-149.0	-147.7	-146.2	-147.2	17.0
44	10/15/84	-148.5	-148.0(2)	-	-	13.8
44	Averages	-148.7	-147.6	-146.1	-147.6	18.4
46	10/27/84	-148.4	-146.6	-145.7	-147.2	15.4
46	10/28/84	-148.1	-147.1	-146.0	-147.5	19.5
46	10/29/84	-148.2	-147.1	-	-	11.8
46	Averages	-148.2	-146.9	-145.8	-147.3	15.6
Averages, Normalized (to 44 Hz)		-148.6	-147.5	-146.0	-147.2	14.7
Predicted 44-Hz Averages		-148.6	-147.3	-145.9	-147.3	15.2

during the day and -2.5 dB at night. Inserting these values in equation (14) results in predicted 44-Hz Connecticut average field strengths of -145.9 dBA/m during the day, -147.3 dBA/m during the transition periods, and -148.6 dBA/m at night. Referring to tables 3 and 4, we see that the predicted and measured 44-Hz average field strengths are almost identical.

The average 1983-84 night-to-day relative-phase variation ($\Delta\phi$) was 14.7 deg (table 4). This corresponds to an average difference in the night-to-day relative-phase velocity ratio ($\Delta(c/v)$) of 0.174, which is almost identical to the 0.18 average value (1.32 - 1.14) inferred from the 1970-72 measurements.

CONCLUSIONS

In this report, we have presented the results of 23 days of 45-Hz-band Connecticut measurements taken during 1983-84. We have shown that the average measured field strengths were in excellent agreement with previous 45-Hz-band measurement results during daytime, transition period, and nighttime propagation conditions.

The average night-to-day relative-phase variation was 14.7 deg. This corresponds to an average difference in the night-to-day relative-phase velocity ratio of 0.174, which is almost identical to the previously inferred value of 0.18.

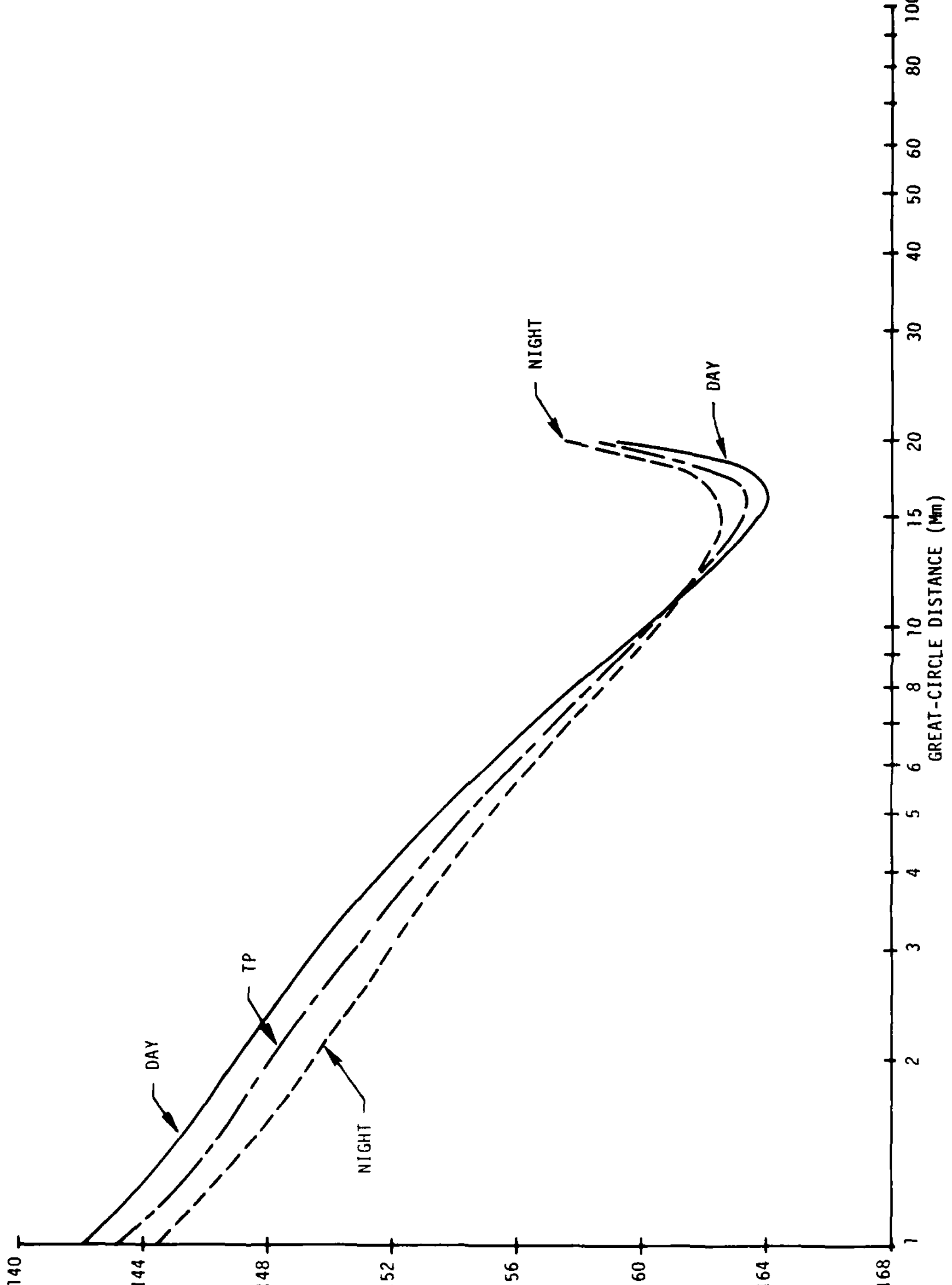

Figure 1. Magnitude of H_ϕ Versus Range (f = 45 Hz, WTF Omni)

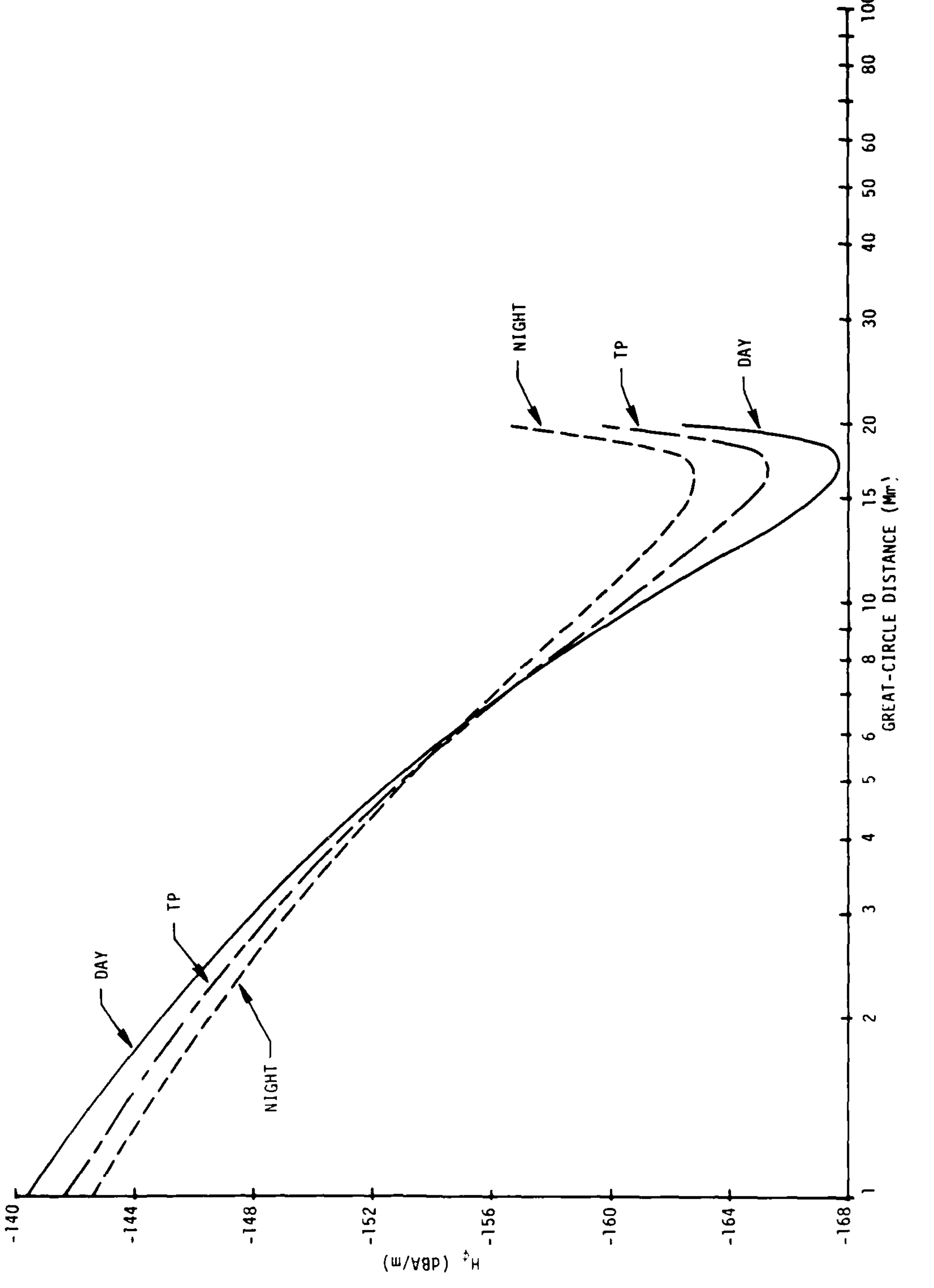

Figure 2. Magnitude of H_ϕ Versus Range (f = 75 Hz, WTF Omni)

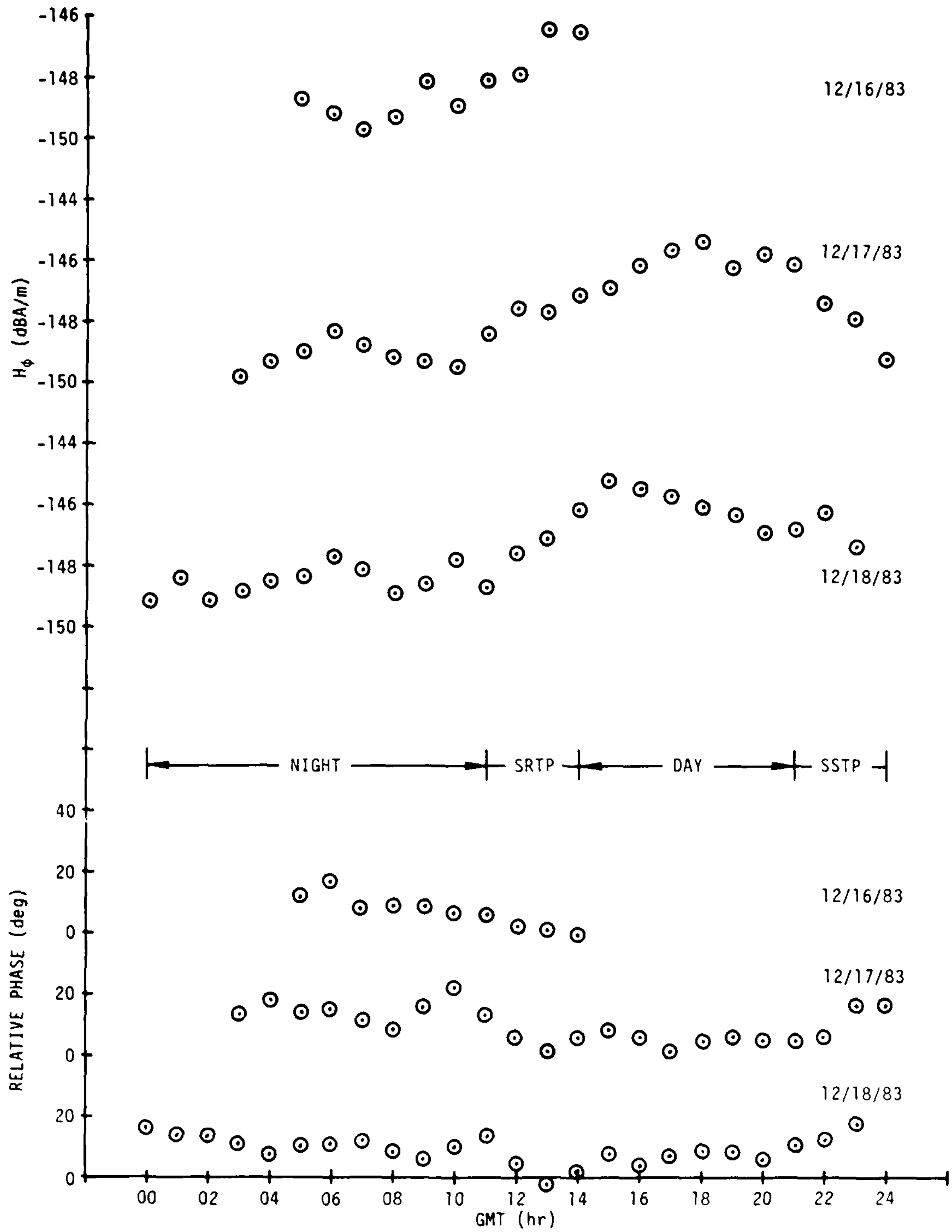

Figure 3. Connecticut 44-Hz Field Strength Versus GMT, 16 Through 18 December 1983 (Normalized to I = 300 A and ϕ = 291 deg)

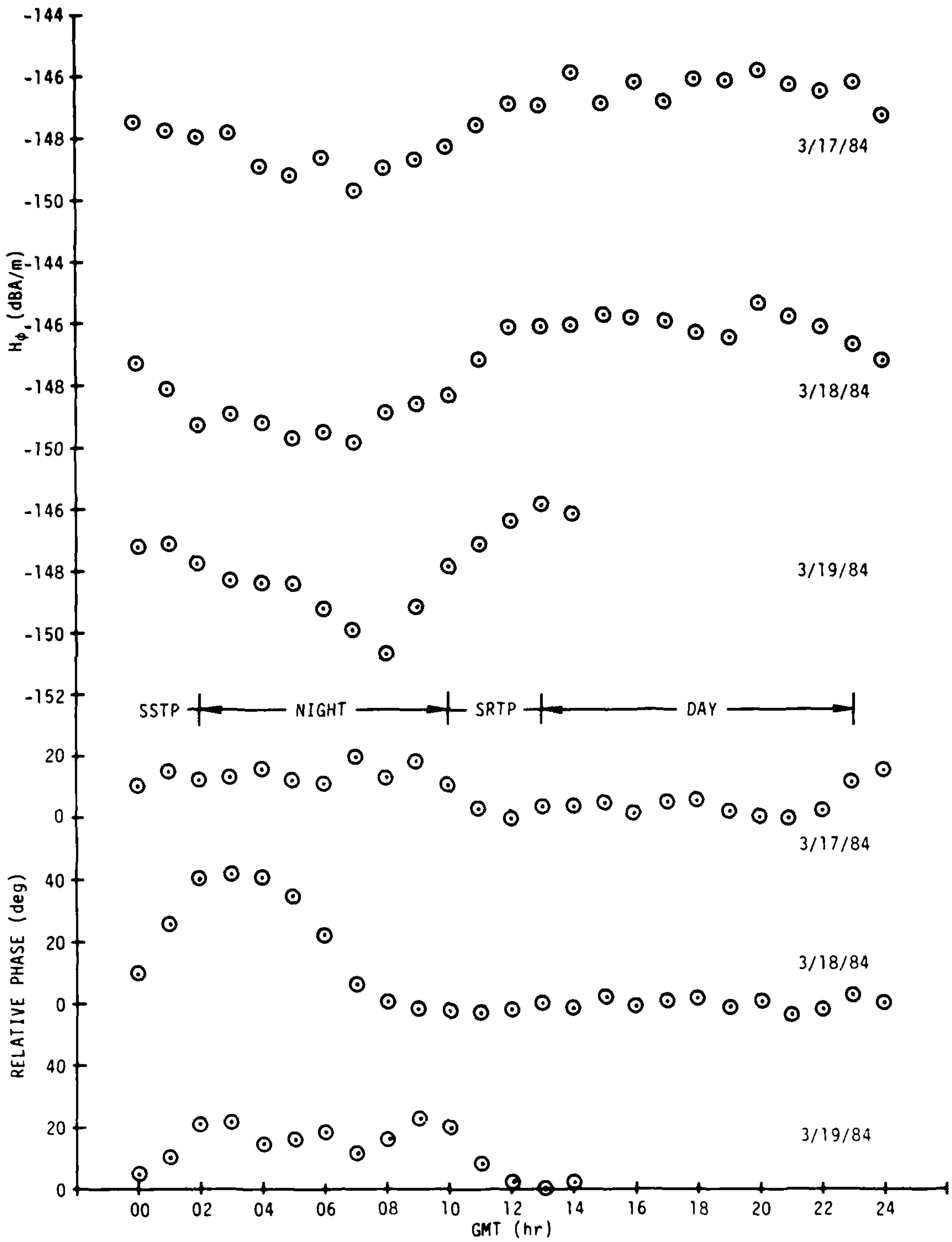

Figure 4. Connecticut 44-Hz Field Strength Versus GMT, 17 Through 19 March 1984 (. = 291 deg, I = 300 A)

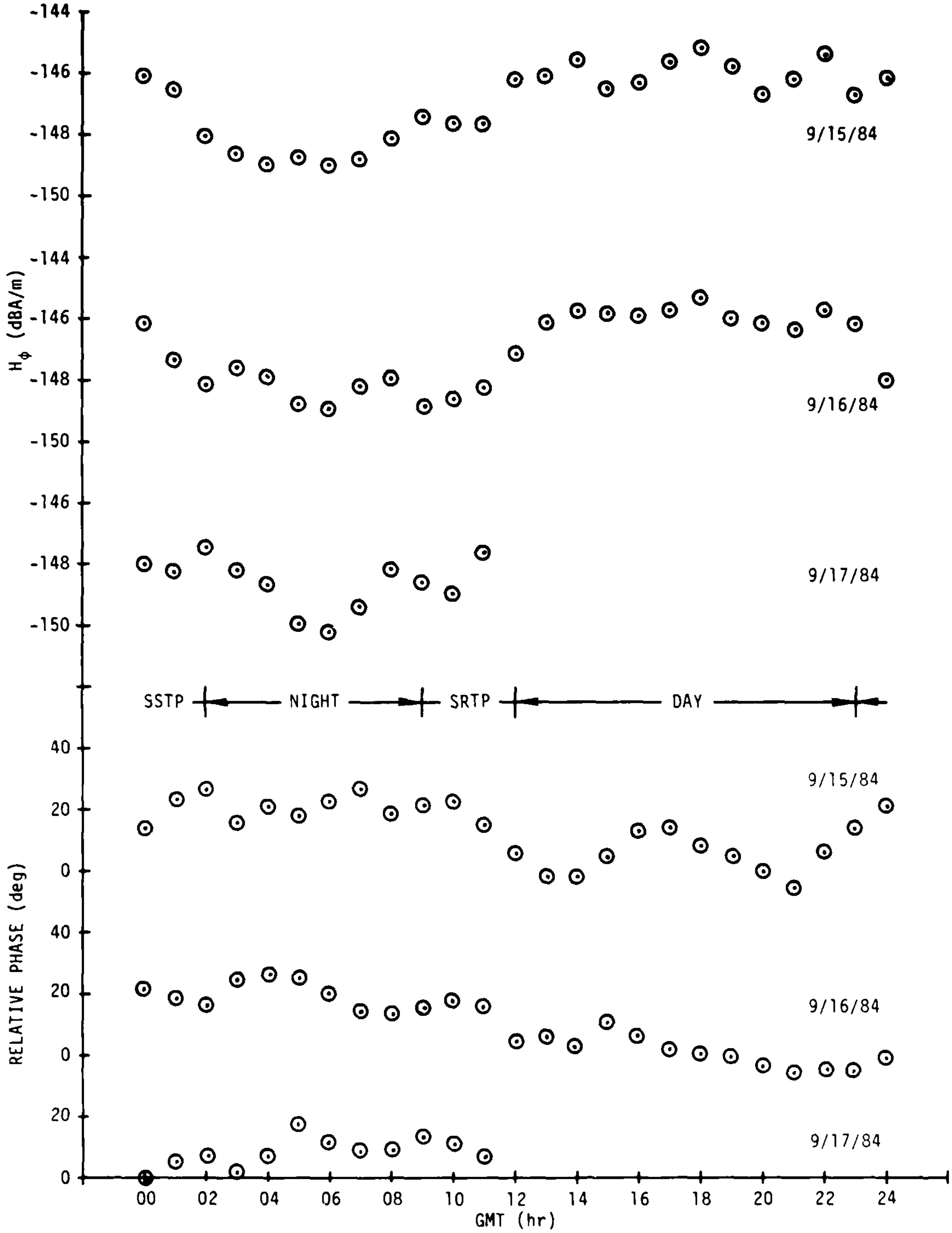

Figure 5. Connecticut 44-Hz Field Strength Versus GMT, 15 Through 17 September 1984 (. = 291 deg, I = 300 A)

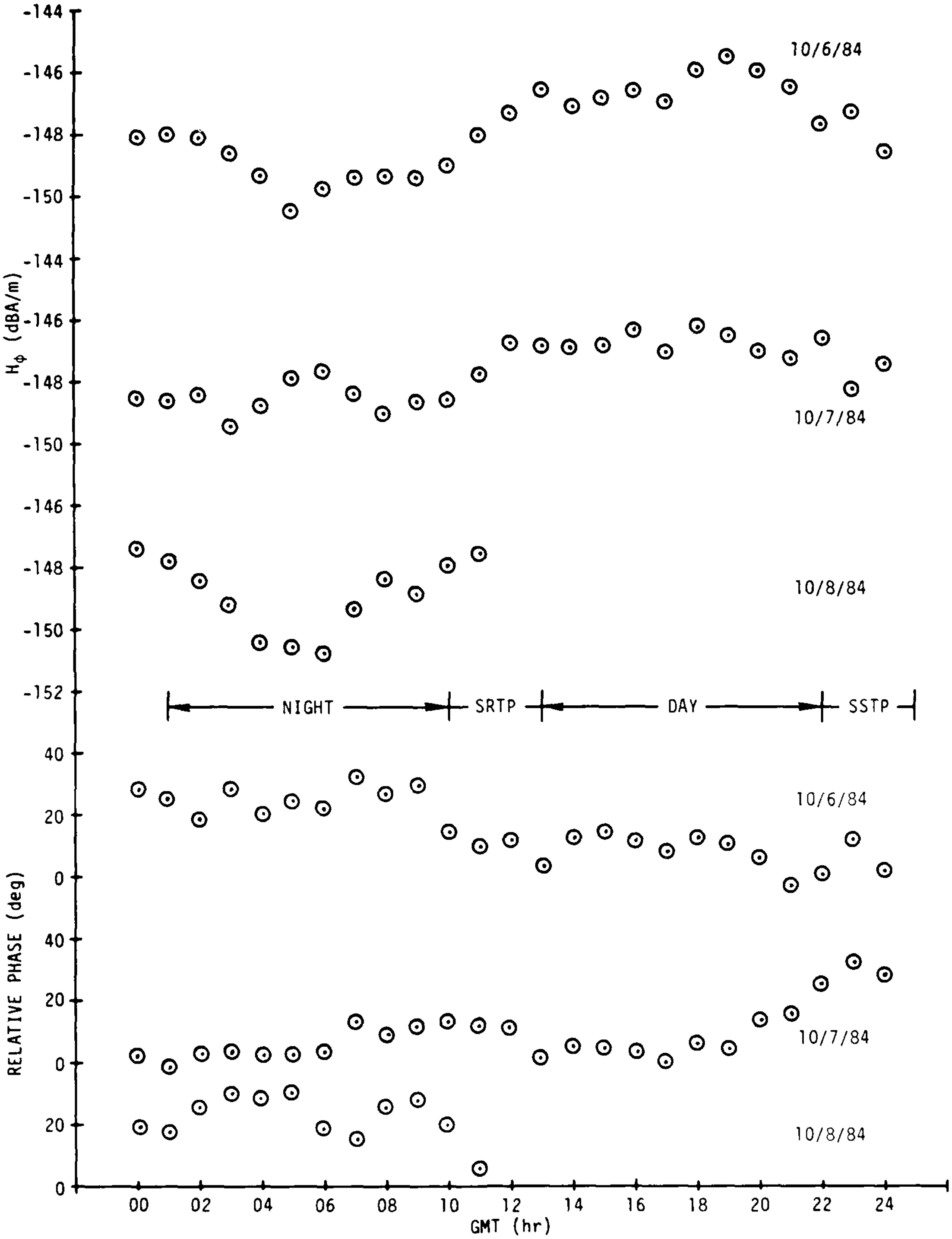

Figure 6. Connecticut 42-Hz Field Strength Versus GMT, 6 Through 8 October 1984 (. = 291 deg, I = 300 A)

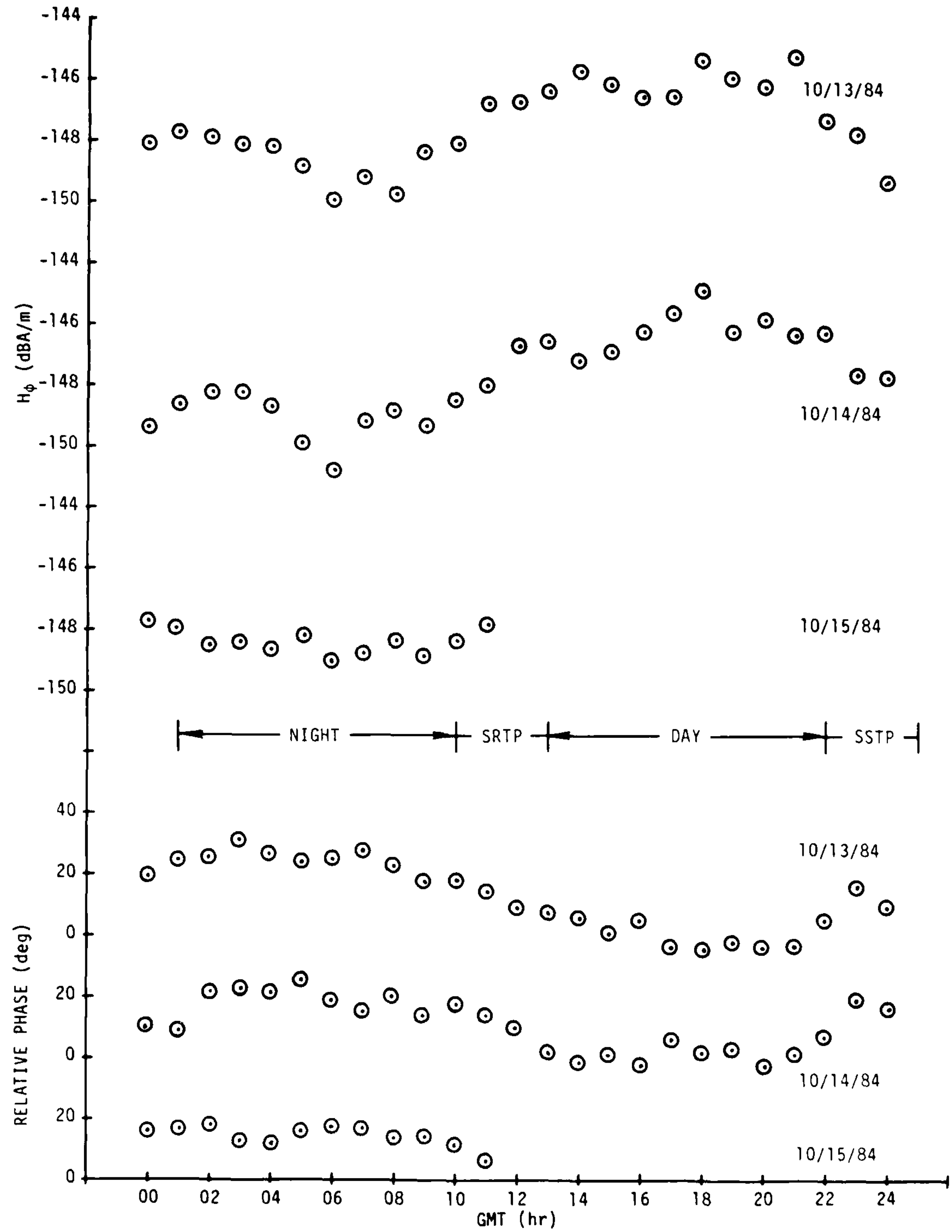

Figure 7. Connecticut 44-Hz Field Strength Versus GMT, 13 Through 15 October 1984 (ϕ = 291 deg, I = 300 A)

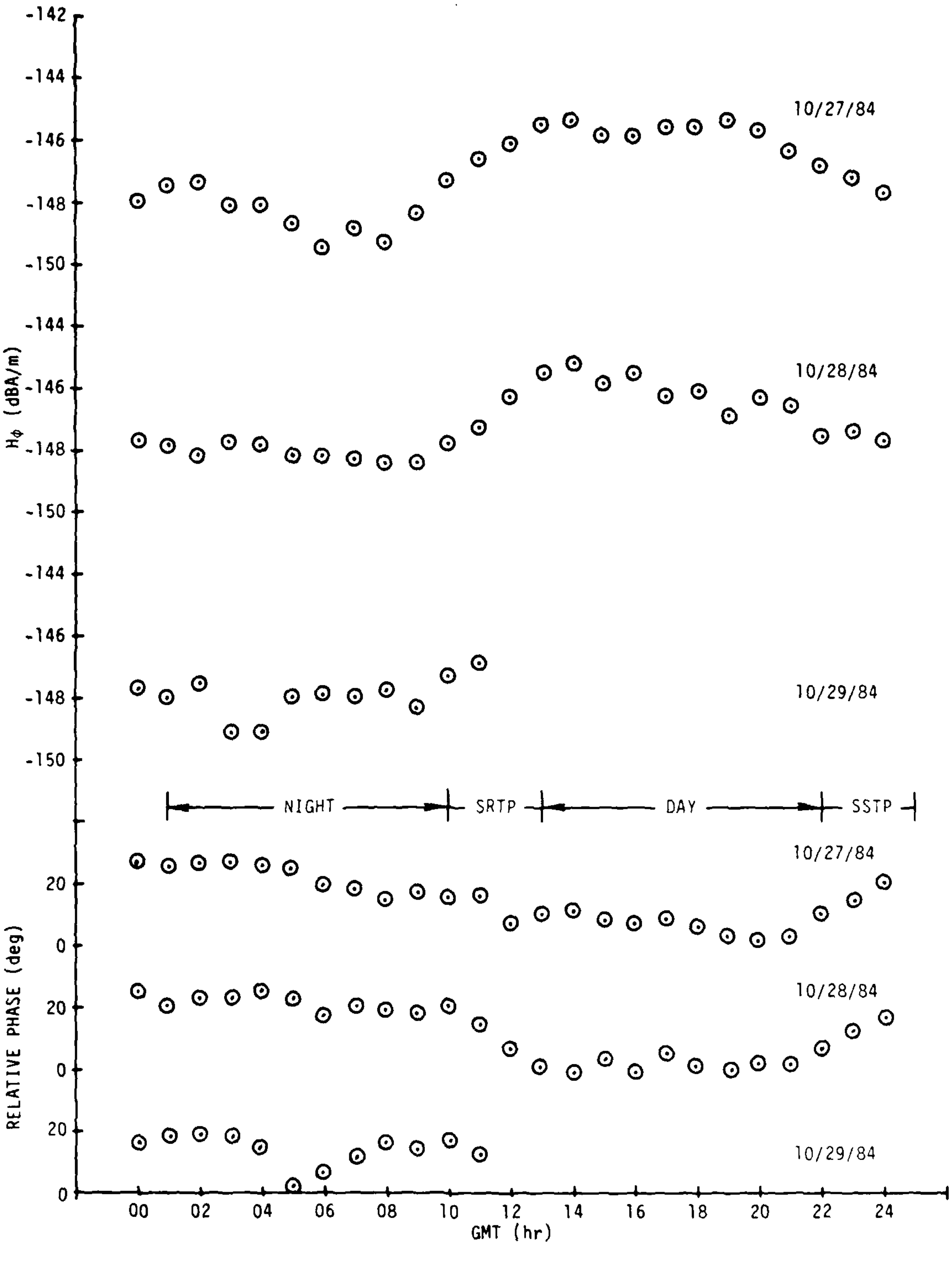

Figure 8. Connecticut 46-Hz Field Strength Versus GMT, 27 Through 29 October 1984 (ϕ = 291 deg, I = 300 A)

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